Prediction of Coherent Structures, Intermittency, and Mixing in the Surface Layer of the Ocean

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LONG -TERM GOAL

I hope to place the dynamics of the mixed layer in the context of sound physical theory with predictive capability. The ultimate aim is to formulate a usable, three-dimensional, unsteady mixed layer theory that incorporates the effects of surface waves, density variation, and models breaking waves and unresolved motions.

OBJECTIVES

My work seeks to describe the mixing and coherent patterns in the wind-driven OSML, on time scales from minutes and larger. The observable coherent patterns are mainly due to Langmuir circulation (LC) or thermal convection, and these mechanisms are responsible for a significant fraction of the mixing. Surface waves and shear are believed to be responsible for Langmuir circulation, and thus this mechanism is particular to systems with a free surface, such as the OSML, while thermal convection is generic and widely studied. My research has concentrated on LC, but within a framework that incorporates thermal convection. I try to understand the patterns formed, including understanding what causes pattern variations within a given LC field, and to characterize the statistical variation of the spatial and temporal behaviors that can be calculated by our theoretical description. The effects of these motions on momentum and heat transport, and on Lagrangian particle transport are key cobjectives of the work.

APPROACH

I develop and work with a range of theoretical models. The one with the most detailed physics is large eddy simulation (LES) with surface wave effects represented by the model due to Craik and Leibovich. LES allows the computation of flows with minimal assumptions about the turbulence. Feasible LES computations are not possible, however, over extended spatial regions, and therefore have limited capability to represent pattern formation questions. These require the use of (pattern formation) models (PFM) with less physical detail, and these have been developed from the full equations. I exercise both classes of models, LES and PFM, by computing examples with parameters corresponding to “typical” oceanographic conditions, or incorporating observational wave and surface flux data. The numerical solution of LES and PFM result in chaotic solutions, and the resulting data is analyzed to produce statistical characterizations.

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WORK COMPLETED

Pattern formation in the unstable Ekman layer provides a classical connection to that arising in LC with Coriolis acceleration included (the latter being the Ekman layer with surface wave effects incorporated. The nonlinear Ekman layer instability itself had not previously been explored, and we have now done this.

We also have successfully extended this to include the stability and nonlinear pattern formation of the Ekman/Langmuir layer, that is, with both Coriolis acceleration and surface wave effects. A preliminary version of this work is reported in the PhD thesis of T. Haeusser. More needs to be done, and we hope to be able to give a comprehensive account in the coming year.

The nonlinear interactions of a Langmuir circulation field and internal waves (IW) has been analyzed within the context of two-layer, two-dimensinal model. This work is being done by Greg Chini as part of his PhD research. A preliminary account of this work was given at the 1998 Ocean Sciences Meeting, and we are making good progress towards a better understanding of this problem.

Computations in stratified media of great depth frequently require the choice of a computational domain that includes an open boundary where boundary conditions must be imposed. These must preclude artificial internal wave reflections. A radiation condition due to Klemp & Durran (1983) at NCAR is widely used there and elsewhere. In particular, it was used by Skyllinstad and Denbo (1995) and by McWilliams, Sullivan, and Moeng's (1997) LES computations of LC. The validity of this condition for LES was examined.

We (Leibovich & Yang, 1998) have archived an LES database for wind stresses and surface wave fields (assuming a JONSWAP wave spectrum, associated with wind speeds of 3, 9, and 15 m/s. If one assumes a mixed layer depth of 50 m, then the database provides three-dimensional turbulent "data" at depth intervals of as little as 25 cm, at time intervals of less than 30 seconds and extending over a one hour period. We have used this database to perform Lagrangian computations of air bubble trajectories and statistics, accounting for gas transfer, for a spectrum of bubble sizes covering the range of less than 10 microns up to a couple of hundred microns. These compations are preliminary to a study of the possible buoyancy effects exerted by microbubbles entrained from breaking waves in the upper 10 meters or so of the free surface. The work was reported by Dawn Chamberlain at the 1998 Ocean Sciences Meeting.

RESULTS

We (Haeusser & Leibovich, 1997a, 1998a) have completed the first study of pattern formation in the classical Ekman layer. The nature of the nonlinear spatio-temporal dynamics depends on latitude, as well as wind speed *and wind direction.*. Our paper gives a comprehensive exploration of the dynamics for all latitudes.

We have also examined the secondary stability of fully nonlinear roll motions in the Ekman layer, and traced out the "Busse balloon". This is reported briefly in Haeusser & Leibovich 1997b, and a full report will be prepared in due course.

A brief report of our preliminary findings for pattern formation in the Ekman/Langmuir layer is given in Leibovich (1998) and in Leibovich et al. (1998), and a full report will be given when additional calculations have been carried out to enable a more complete account of the physics. Such pattern formation studies may, we think, provide an explanation of the so-called “Y-junctions” observed by Farmer & Li (1994), and by Thorpe (1992), among other and possibly more important matters. Y-junctions are locations where LC windrows merge. One would think there should be some rough parity in the number of merging and the number of splitting windrows, but observations indicate a predominance of mergers over bifurcations. The right hand panel in Figure 1 showss computed surface patterns from our pattern formation studies at a particular instant, in the case where Coriolis acceleration is neglected and the corresponding figure 2 below it shows a case where Coriolis is not neglected. In both cases, the wind stress is from left to right. Windrow spacing is adjusted at splits and bifurcations, the sites of which are known in the pattern formation literature as pattern defects. Figure 2 shows the expected effect of Coriolis acceleration in the Northern Hemisphere, the general orientation of windrows is the the right of the wind. The left hand panels in the figures are real (solid lines) and imaginary (broken lines) contours of the instantaneous complex amplitude from which the velocity field is constructed.

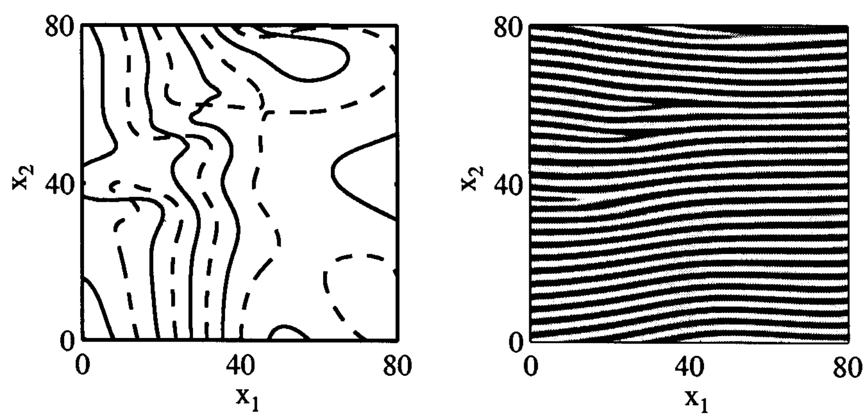

Figure 1

Defects are located at the intersections of these two families of contours. The motion is chaotic in space and time, with the dynamics apparently motivated by the random progress of defects moving through the field. It should be noted that the behavior of the dynamics, that is, whether it is chaotic or not and the dominant spacing of windrows, depends on the *direction* of the applied stress relative to due North. This is a feature that should be

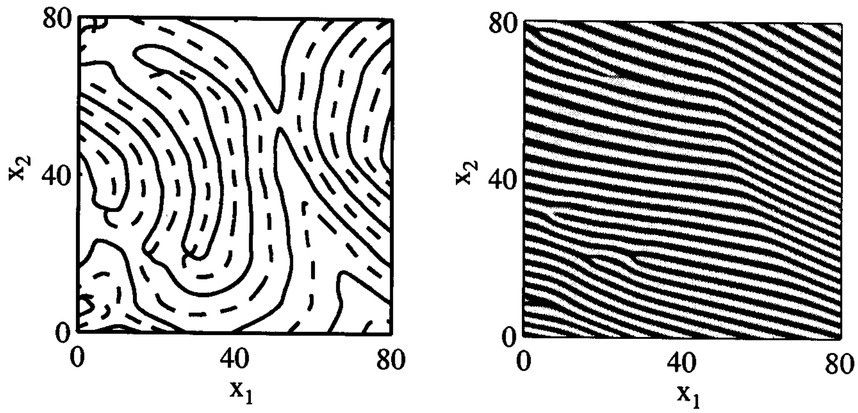

Figure 2

subjected to observational test, and which is unlikely to have been discovered from computations with the primitive set of equations. The pattern formation studies also show that the Coriolis acceleration causes Langmuir circulation and associated windrows to drift sideways. Furthermore, our studies also show that windrows composed of surface flotsam (such as bubbles) may on occasion not be visible, when lateral drift speeds are comparable to the surface convergence speeds. In such cases, coherent vertical mixing is present without the telltale surface signature of the LC causing the mixing. A paper giving the criteria for formation of surface signatures is under preparation (Haeusser & Leibovich, 1998b).

Preliminary results from Greg Chini's investigations of the nonlinear interactions of a Langmuir circulation field and internal waves (IW) show that strong variations of IW and LC can occur due to nonlinear interactions. The implications are being explored.

We (G. Chini and S. Leibovich, 1997, abstract only) have shown that the radiation condition used is incompatible with LES models, and a full paper detailing the discrepancies is in preparation.

IMPACT/APPLICATION

The work outlined above has the potential to tell us

- when Langmuir circulations are present but not detectable by surface Lagrangian tracers,
- what patterns will be present under the more prevalent conditions when tracers due provide a natural flow visualization,
- how the surface signal mignt allow an inference of subsurface mixing activity (for example, by remote sensing) ,
- how internal waves may interact with LC, and how this may lead to large amplitude variability in both LCs and Iws.

All of the above affect mixing of heat, momentum, and material transport in the OSML, with implications on air/sea interaction, large scale ocean and atmospheric modelling, marine biology, and gas transfer.

TRANSITIONS

Our models, especially the underlying Craik-Leibovich model has now been incorporated into computational ocean models by a wide range of groups. The bubble distribution work has been communicated to others. In particular, David Farmer has supplied us with data on observed bubble distributions in LC fields, and we in turn plan to supply him with our simulated data.

RELATED PROJECTS

Together with Amit Tandon, we are attempting to simulate the laboratory experiments of Melville et al. (1998). The conditions of these experiments has been discounted as being beyond the applicability of existing LC theory. Arguments can be given indicating that it is not clear the theory can be discounted in this application, and the correspondence between simulations and experiment will shed light on this matter. Ken Melville has agreed to cooperate in this effort.

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